ACCRETING COMPACT STARS

A unique window on strong gravity

The (fast) timing approach

Didier BARRET
CESR Toulouse, France

Talk given on behalf of

M. Abramowicz, J.L. Atteia, D. Barret, T. Belloni, G. Bignami, H. Bradt, L. Burderi, S. Campana, P. Caraveo, A. Castro-Tirado, D. Chakrabarty, P. Charles, S. Collin, S. Corbel, T. Courvoisier, C. Done, G. Dubus, M. Gierlinski, J. Grindlay, A. Fabian, R. Fender, E. Gourgoulhon, J.M. Hameury, G. Hasinger, C. Hellier, M. van der Klis, P. Kaaret, E. Kendziorra, W. Kluzniak, E. Kuulkers, S. Larsson, J.P. Lasota, P. Lechner, T. Maccarone, D. de Martino, K. Menou, M. Méndez, S. Mereghetti, C. Miller, F. Mirabel, C. Motch, M. Nowak, J.F. Olive, S. Paltani, R. Remillard, J. Rodriguez, R. Rothschild, A. Santangelo, R. Staubert, G. Skinner, L. Stella, L. Strüder, T. di Salvo, R. Sunyaev, M. Tagger, M. Tavani, L. Titarchuk, J. Trümper, G. Vedrenne, N. White, R. Wijnands, J. Wilms, A. Zdziarski, W. Zhang, ...

Mostly from the RXTE community (includes US colleagues)

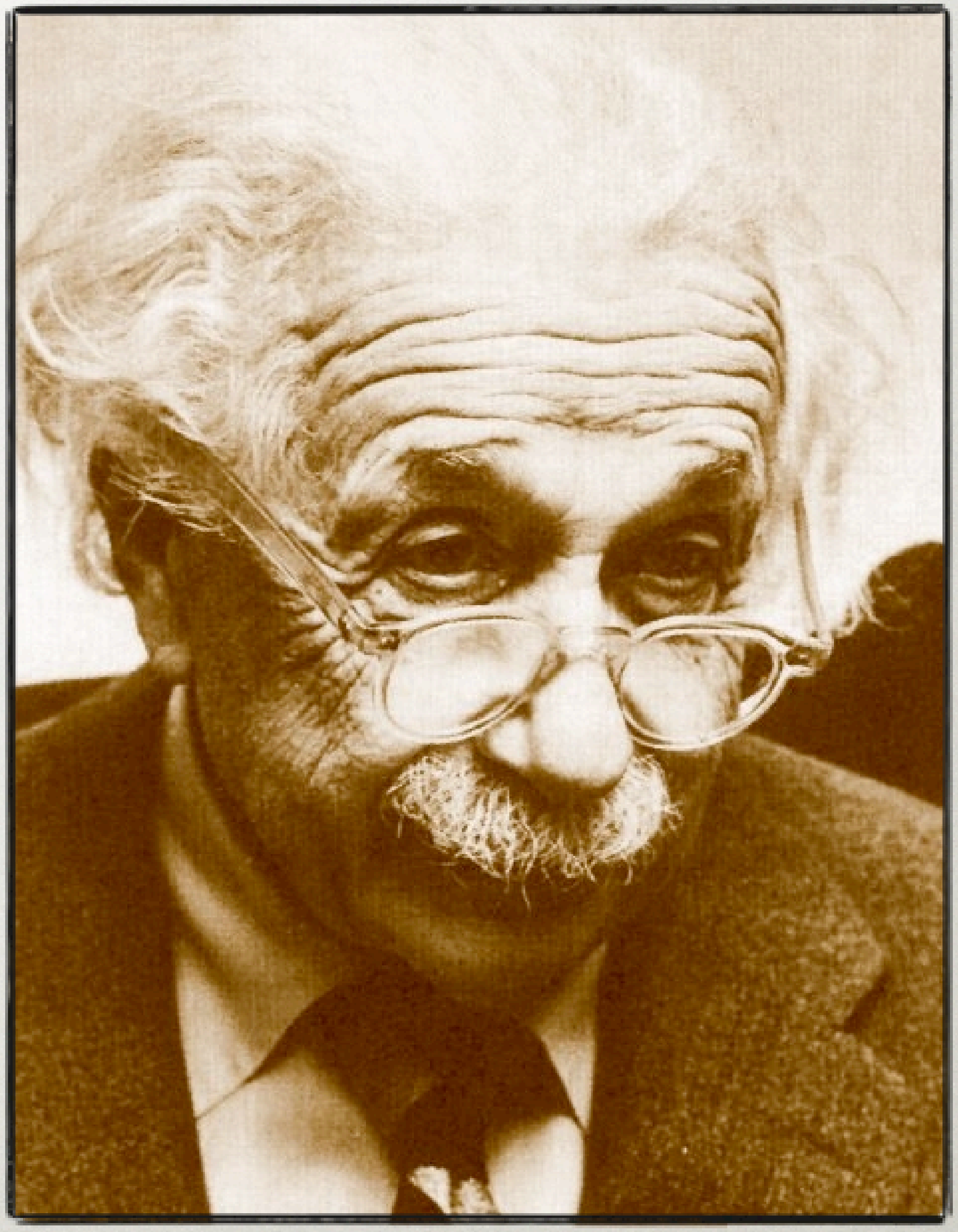
Outline

- General Relativity & Compact stars
- Orbital motions and the innermost stable circular orbit
- Epicyclic motions
- Frame-dragging
- Timing beyond RXTE

GR and compact stars

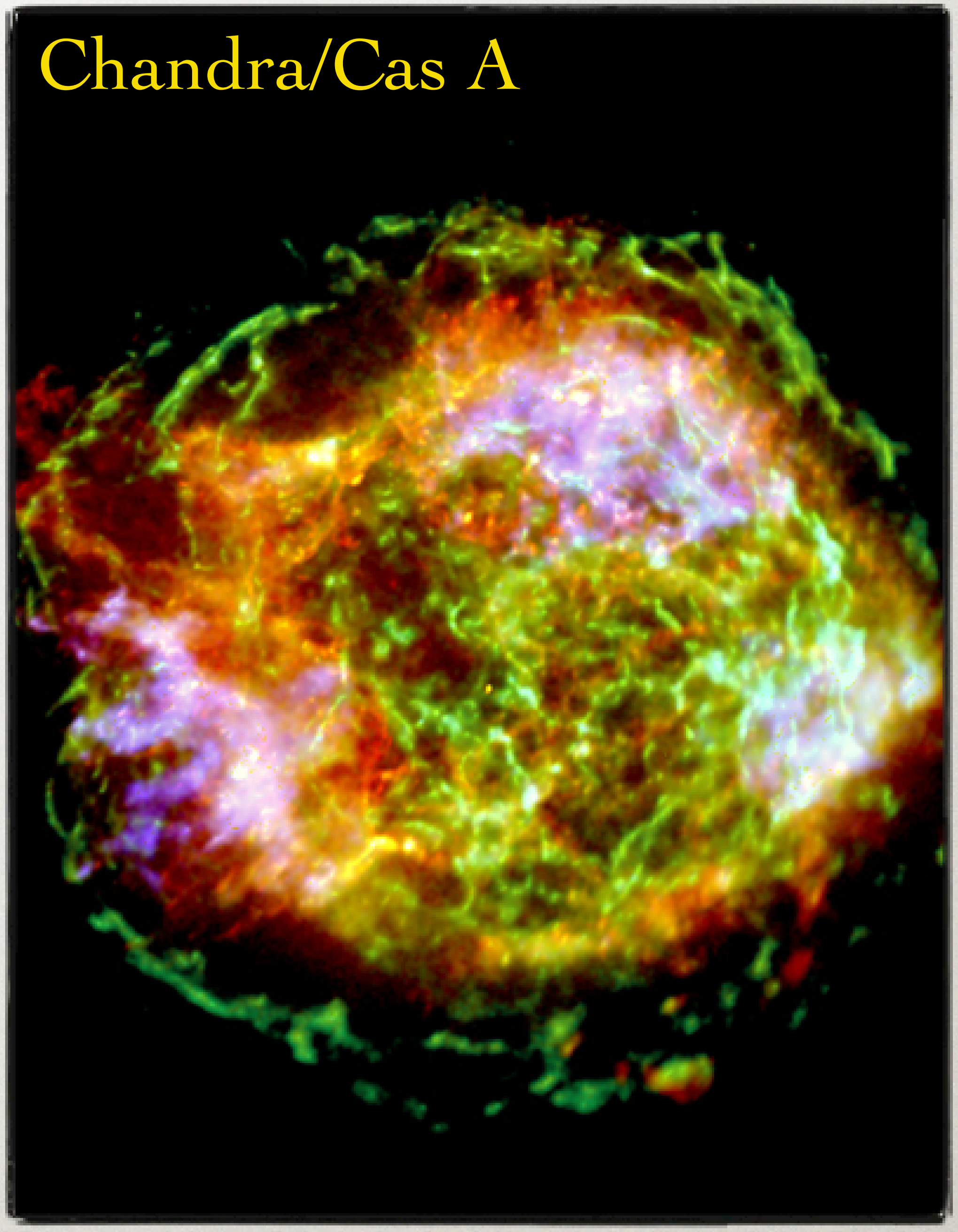
General Relativity

- GR remains the best ever formulated theory of gravitation
- GR has been successfully tested in the weak field regime
- Tests of GR in the strong field regime are required

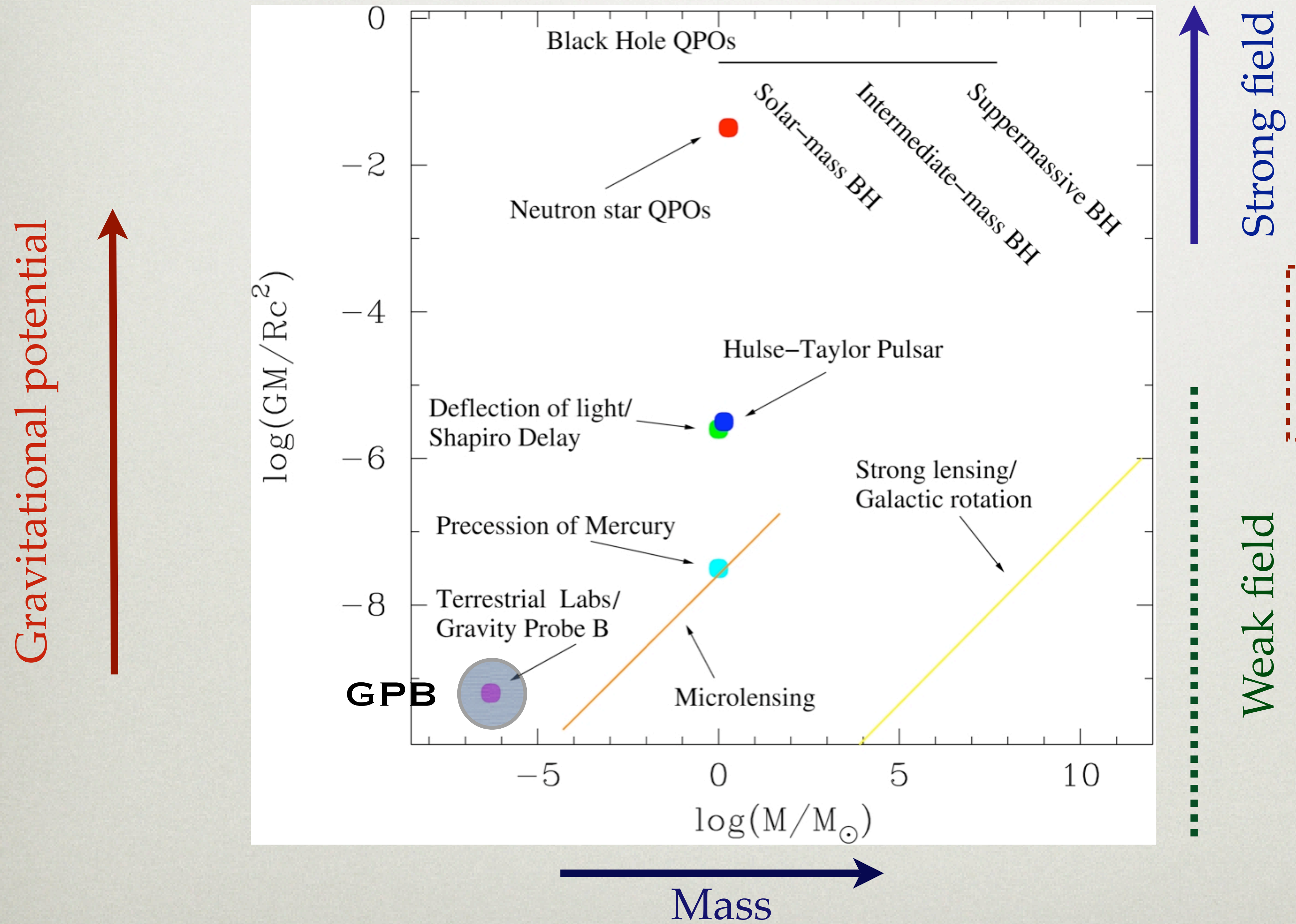


Compact Stars

- End-points of stellar evolution
- Formation associated with the most violent phenomena of the Universe
- Responsible for the enrichment of the Universe in heavy elements
- *Great appeal to the grand public*



The best tools



The most dramatic effects are expected in the strong field regime

Adapted from Psaltis (2004)

Complementarity

- Understanding strong gravity is of fundamental importance
- Several parallel approaches should be followed:
  - X-ray spectroscopy
  - Fast X-ray timing
  - Polarization measurements
  - Gravitational waves
  - Direct black hole imaging: radio, infra-red and ultimately X-rays
- We should use tools of different sizes and masses: X-ray binaries with neutron stars, stellar mass black holes and AGNs

Towards a common goal

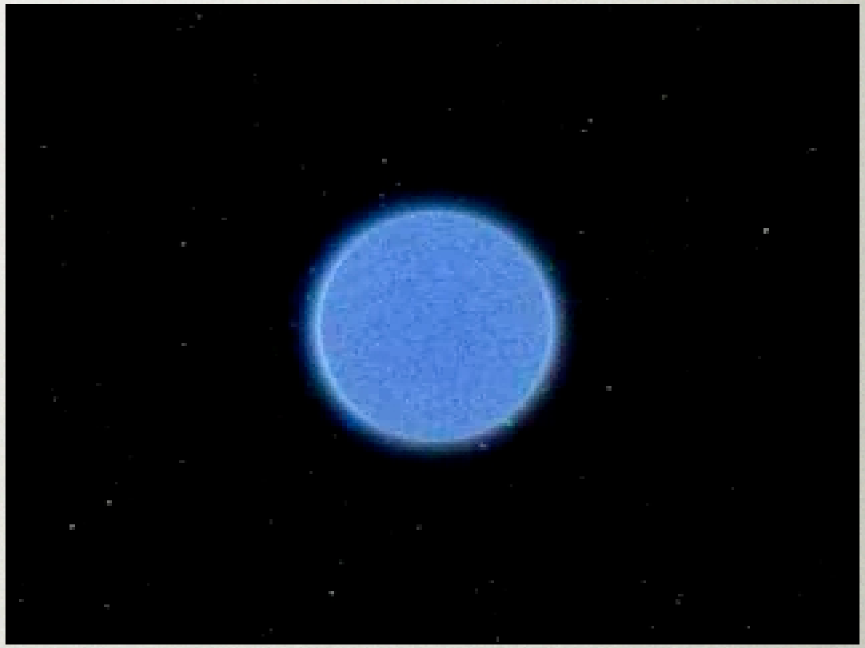
- All these parallel approaches for the same goal:
  - Testing GR in the strong field limit
  - Understanding the nature of space and time
- With the by products of:
  - Getting constraints on the fundamental parameters of compact stars, e.g. black hole spin
  - Determining the properties of matter at supra-nuclear density
  - Getting a better understanding of accretion disk physics (relevant to many fields of modern astrophysics)

The RXTE breakthrough

The power of X-ray timing

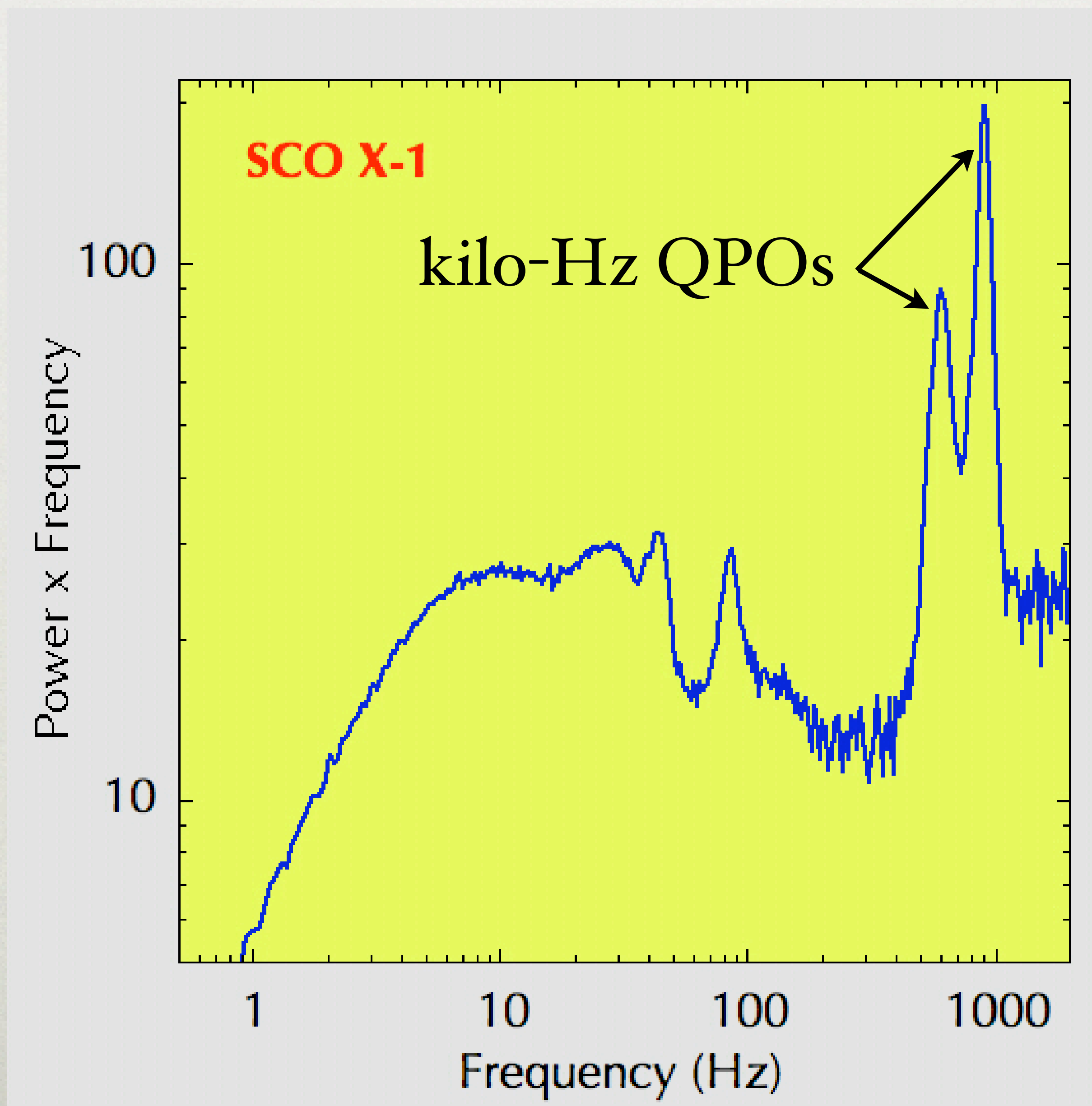
- 90% of the energy will be radiated, predominantly in X-rays, within the last 100 km
- Dynamical timescales of the accretion flow:
  - 0.1 ms at 15 km of a 1.4 Msol neutron star
  - 1 ms at 100 km (3Rs) of a 10 Msol black hole

  X-ray (sub)-ms variability probes the motion of matter in the strong field region



RXTE BREAKTHROUGH

RXTE has demonstrated that the X-ray emission of accreting compact objects varies on the dynamical timescales

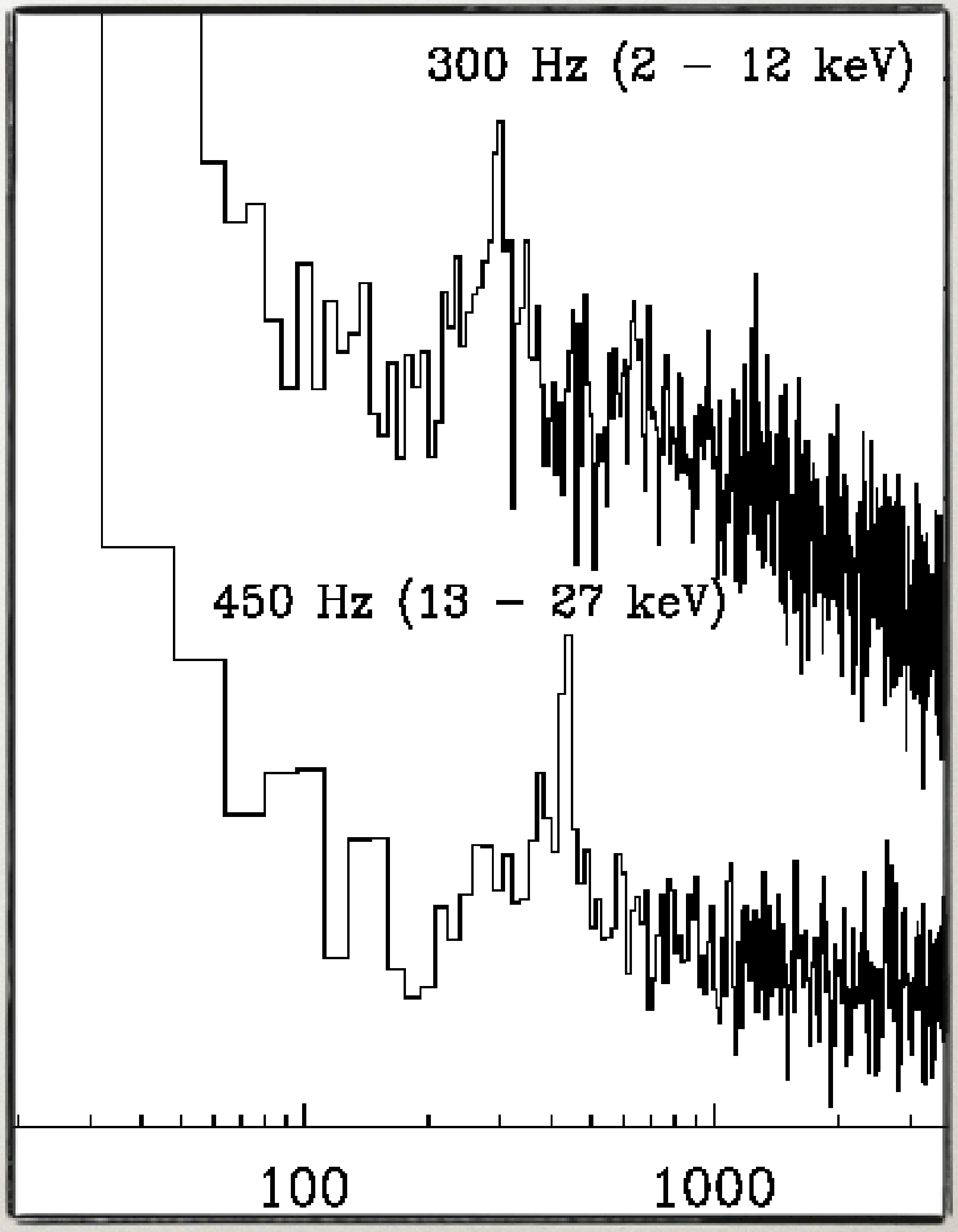


Van der Klis (2004) - Remillard (2004)

KILO-Hz QUASI-PERIODIC OSCILLATIONS

- Detected in ~20 neutrons stars - frequencies vary from ~100 to 1000 Hz
- Detected in a handful of stellar mass black holes with constant frequencies (~100 Hz, with a possible 3:2 ratio)
- Strong energy dependency
- Varies with spectral, luminosity states, etc.

WEAK BH QPOs



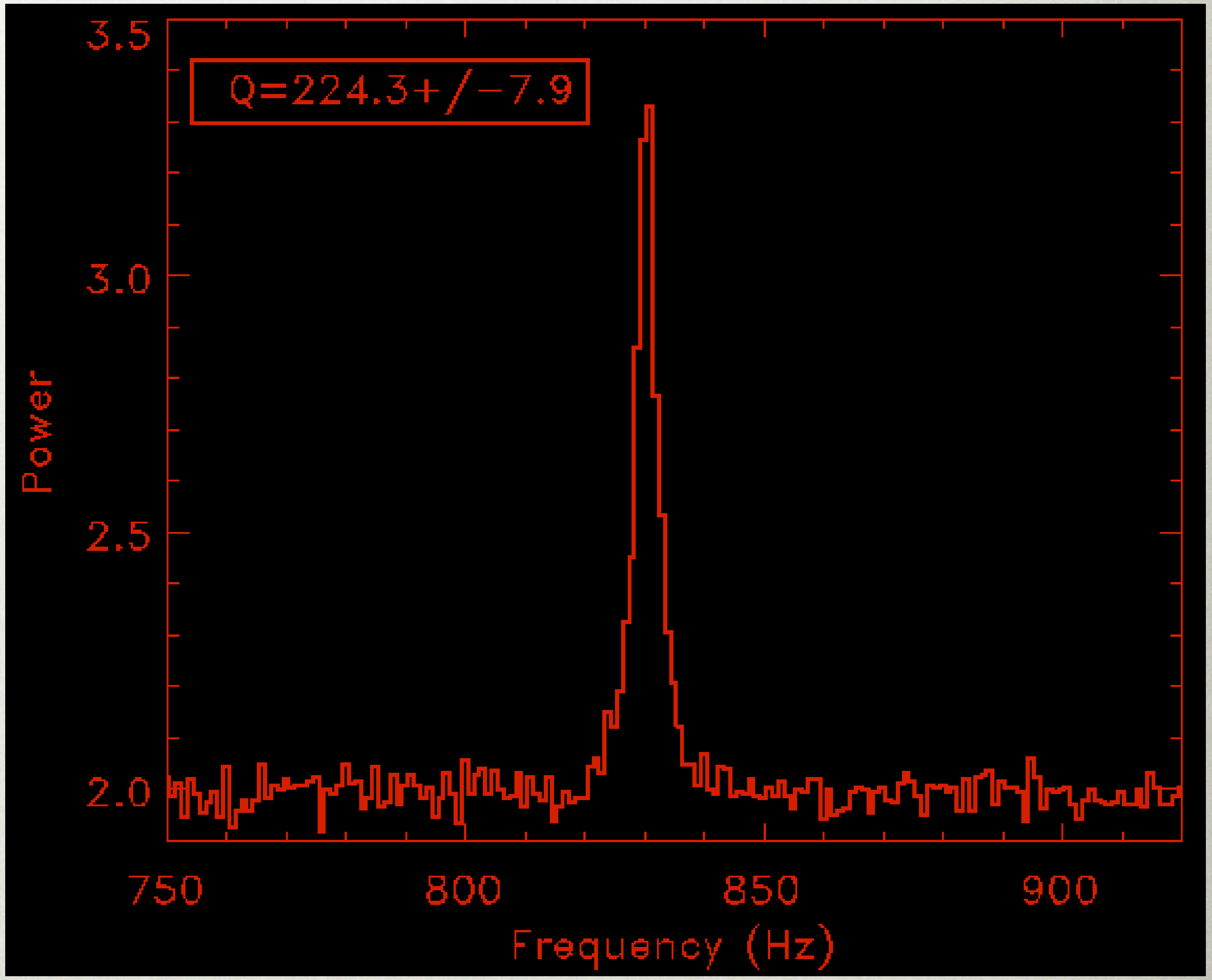
STROHMAYER (2001)

Orbital motion

Orbital motion

- The accretion disk is a natural source of periodicities (Keplerian motion)
- QPOs have frequencies expected from the inner accretion disk
- High Q signals
- It is natural (and most models do) to identify QPOs with orbital motion at a preferred radius of the disk (inner disk radius)

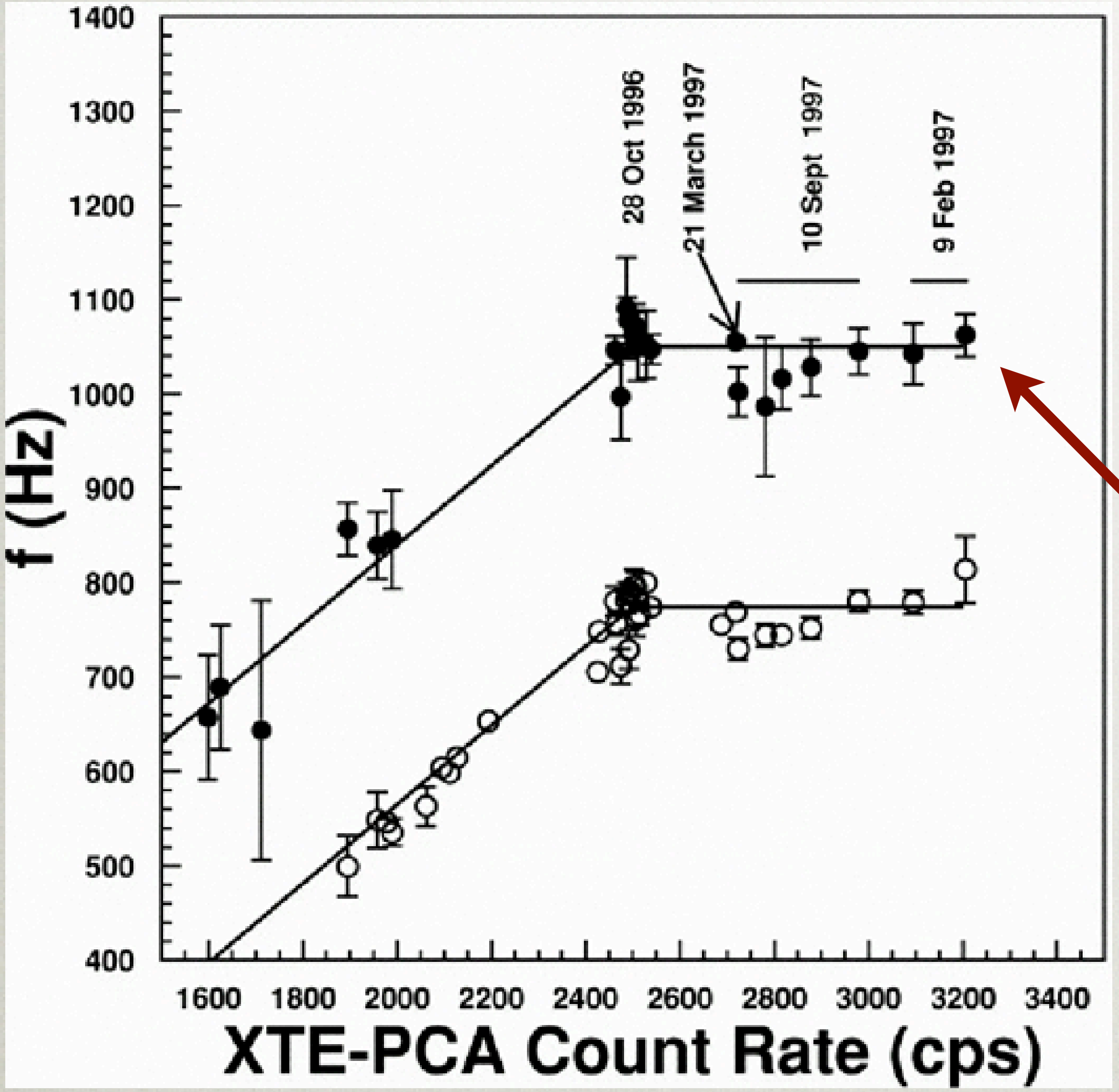
$$\nu_K = \sqrt{GM/r^3}/2\pi \approx 1184\,\mathrm{Hz}\left(\frac{r}{15\,\mathrm{km}}\right)^{-3/2} m_{1.4}^{1/2} \approx 184\,\mathrm{Hz}\left(\frac{r}{100\,\mathrm{km}}\right)^{-3/2} m_{10}^{1/2}$$



Innermost stable circular orbit

- Key prediction of strong-gravity General Relativity - There exists a minimum radius beyond which no stable orbital motion is possible
- This radius is a function of the mass and spin of black hole
- The highest possible orbital frequency in the disk is at the radius of the ISCO

Orbital motion at the ISCO?



Ceiling of frequency predicted when the ISCO is reached

$$\nu_{\rm isco} \approx (1570/{\rm m}_{1.4})\,{\rm Hz}$$

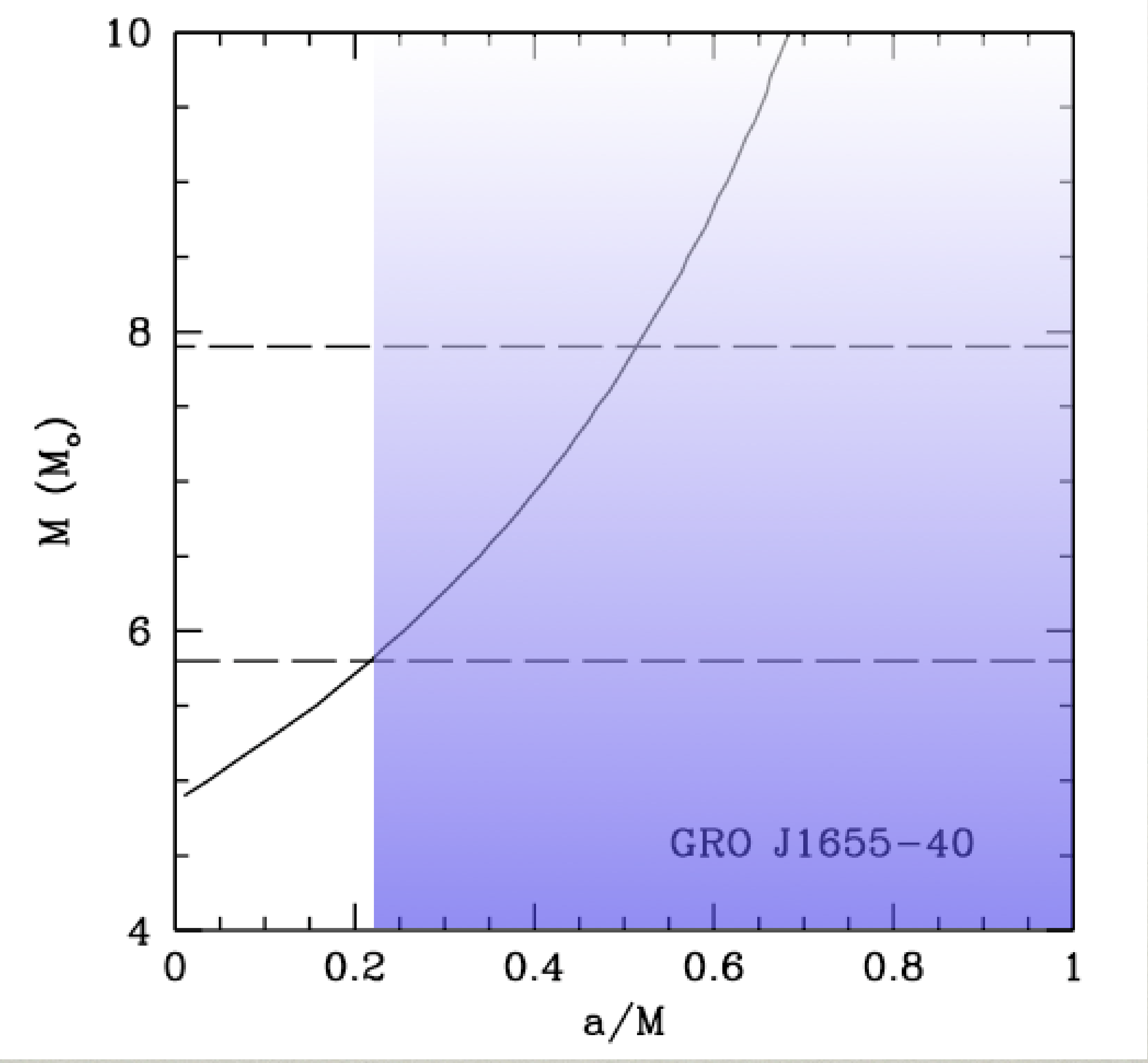
$${\rm M} \sim 2.2\ {\rm M}_\odot$$

But seen in only one system so far! and disputed results

Zhang et al. (1998)

Constraining BH spin

$$\nu_{\rm QPO} \leq \nu_k(R_{\rm ISCO}) \Longrightarrow a/M > 0.2$$



Psaltis (2004)

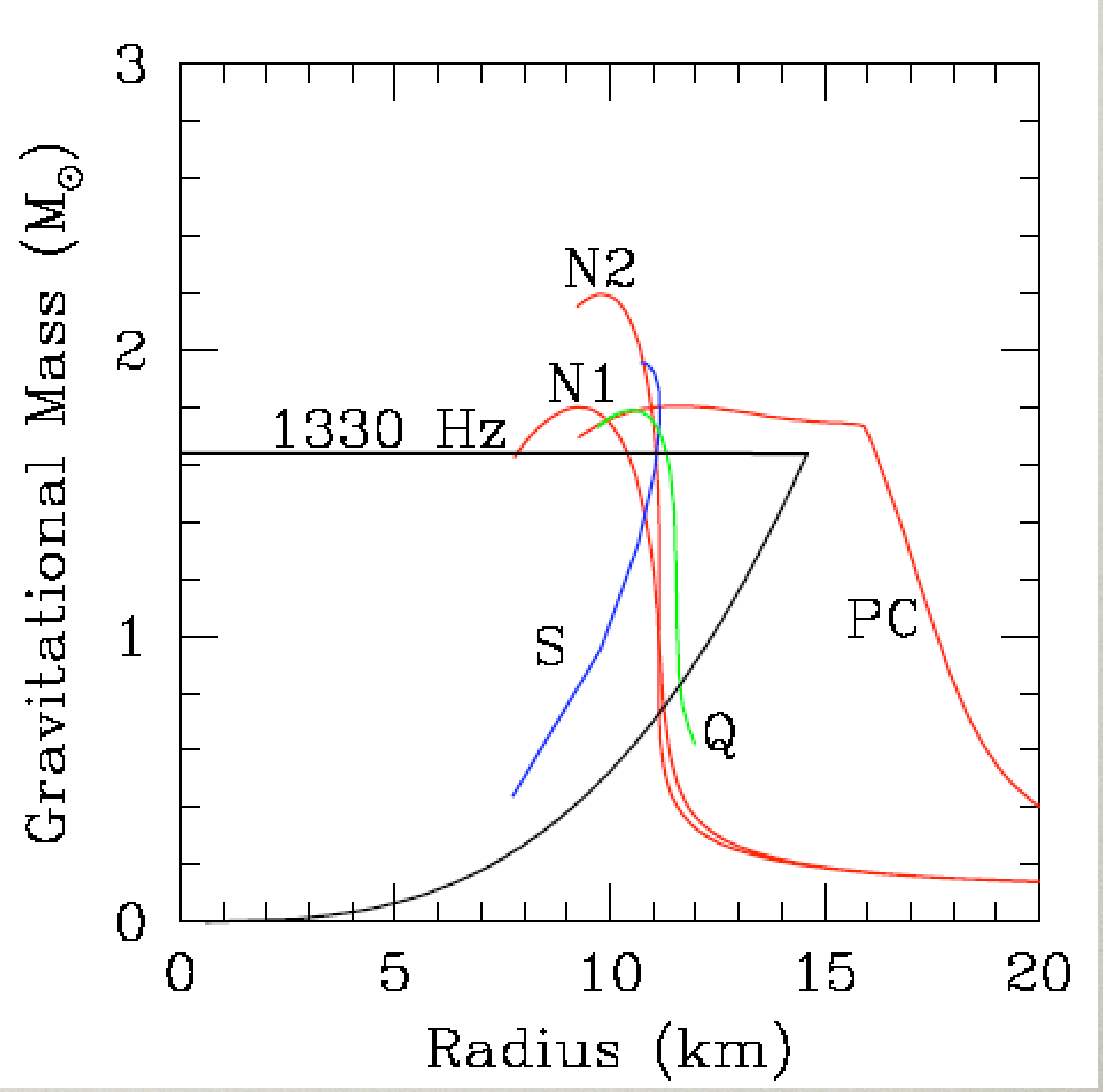
Dense matter

Constraints from orbital frequencies

$$\nu_{\rm orb} \Longleftrightarrow R_{\rm orb}$$

$$R_* < R_{\rm orb}$$

$$R_{\rm orb} > R_{\rm ISCO} = \frac{6GM}{c^2}$$

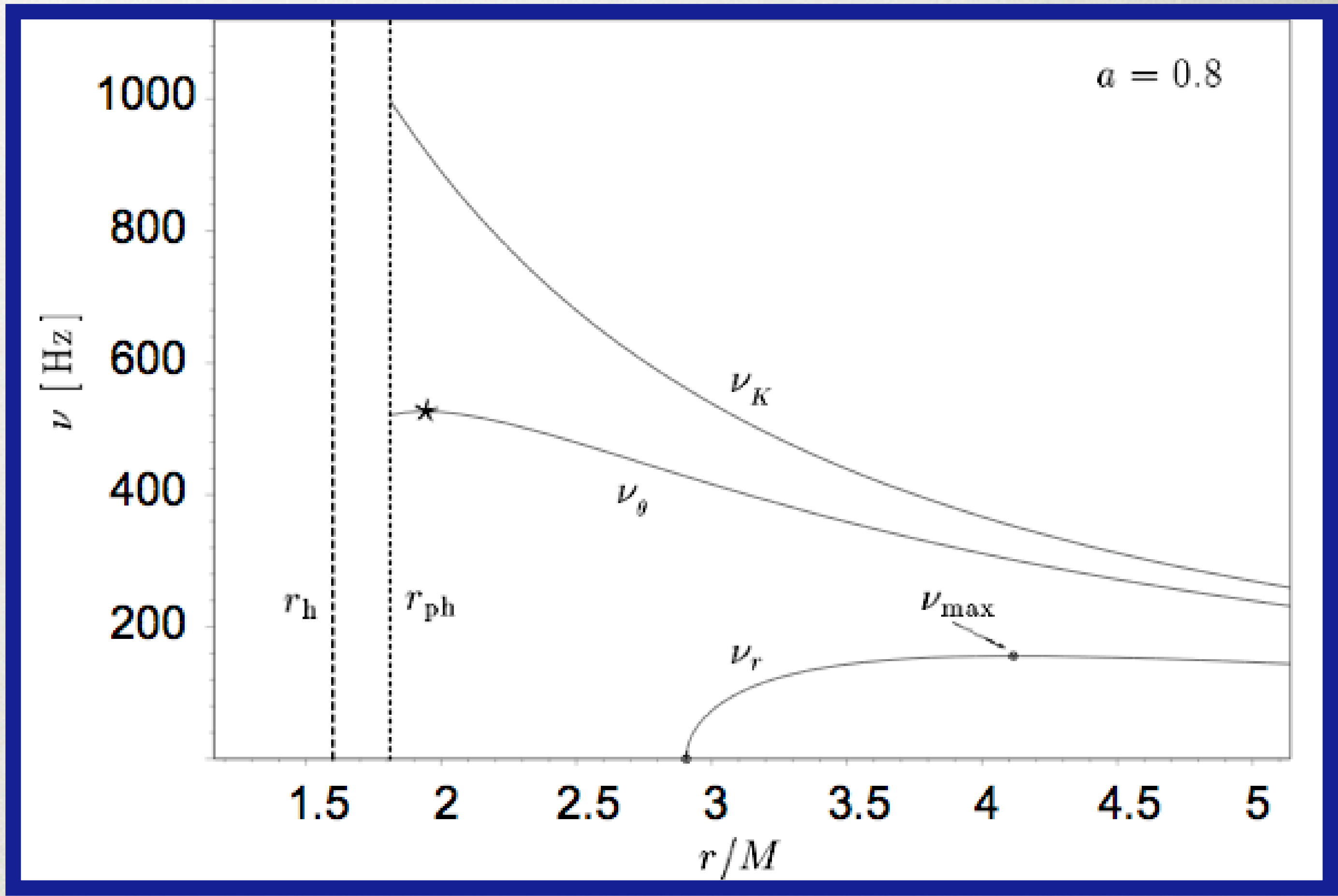


Miller, Lamb & Psaltis (1998) - Miller (2004)

Epicyclic motion

3 GR frequencies

- In GR, test particle orbits are characterized by 3 frequencies:
  - Azimuthal
  - Radial epicyclic
  - Vertical epicyclic
- All three frequencies depend on the mass, spin and orbital radius

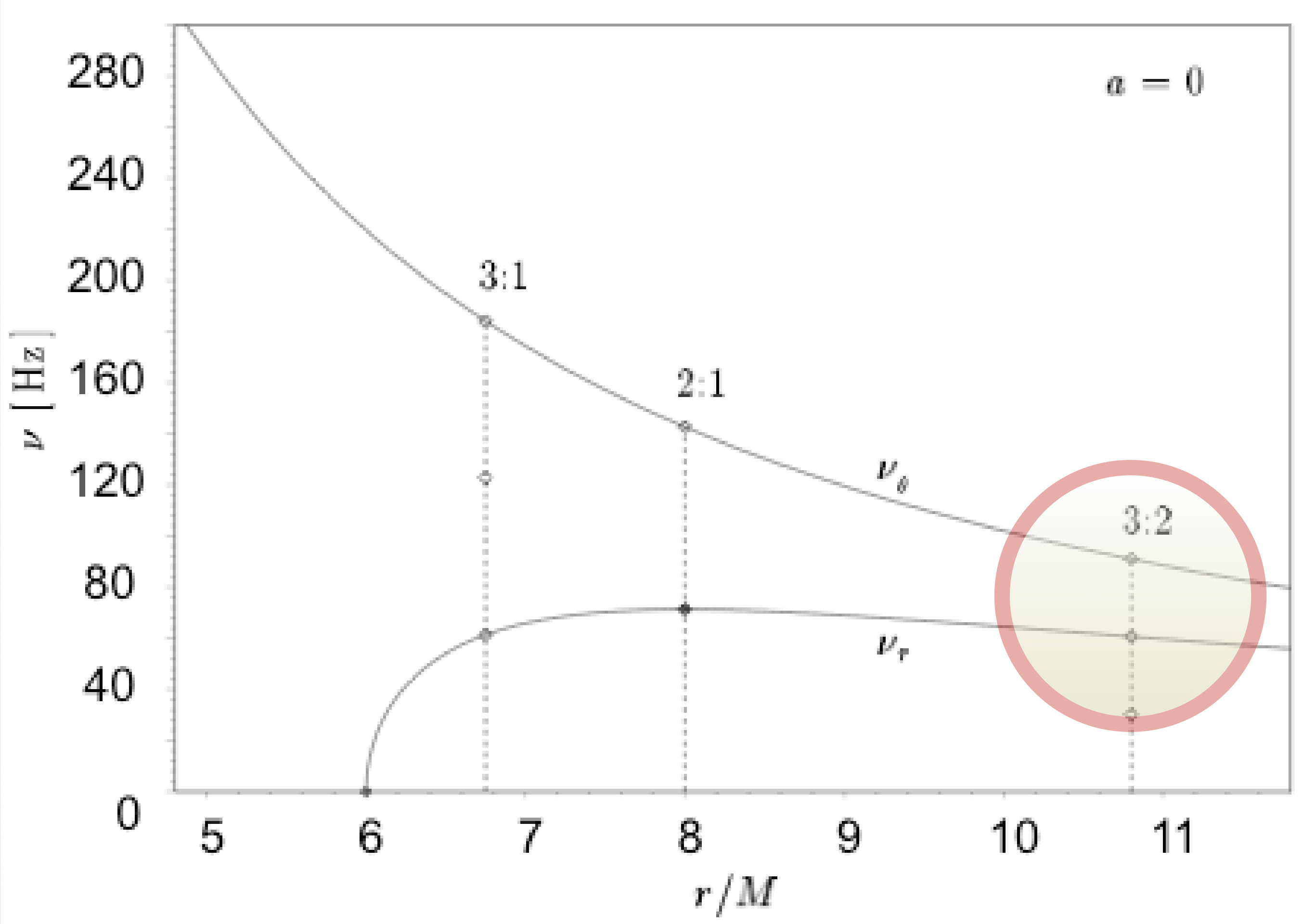


Abramowicz & Kluzniak (2004)

Relativistic resonance

Resonance can occur between relativistic orbital and epicyclic frequencies

Proposed to explain the 3:2 ratios observed in BHs, and the clustering of twin NS QPOs around the same ratio



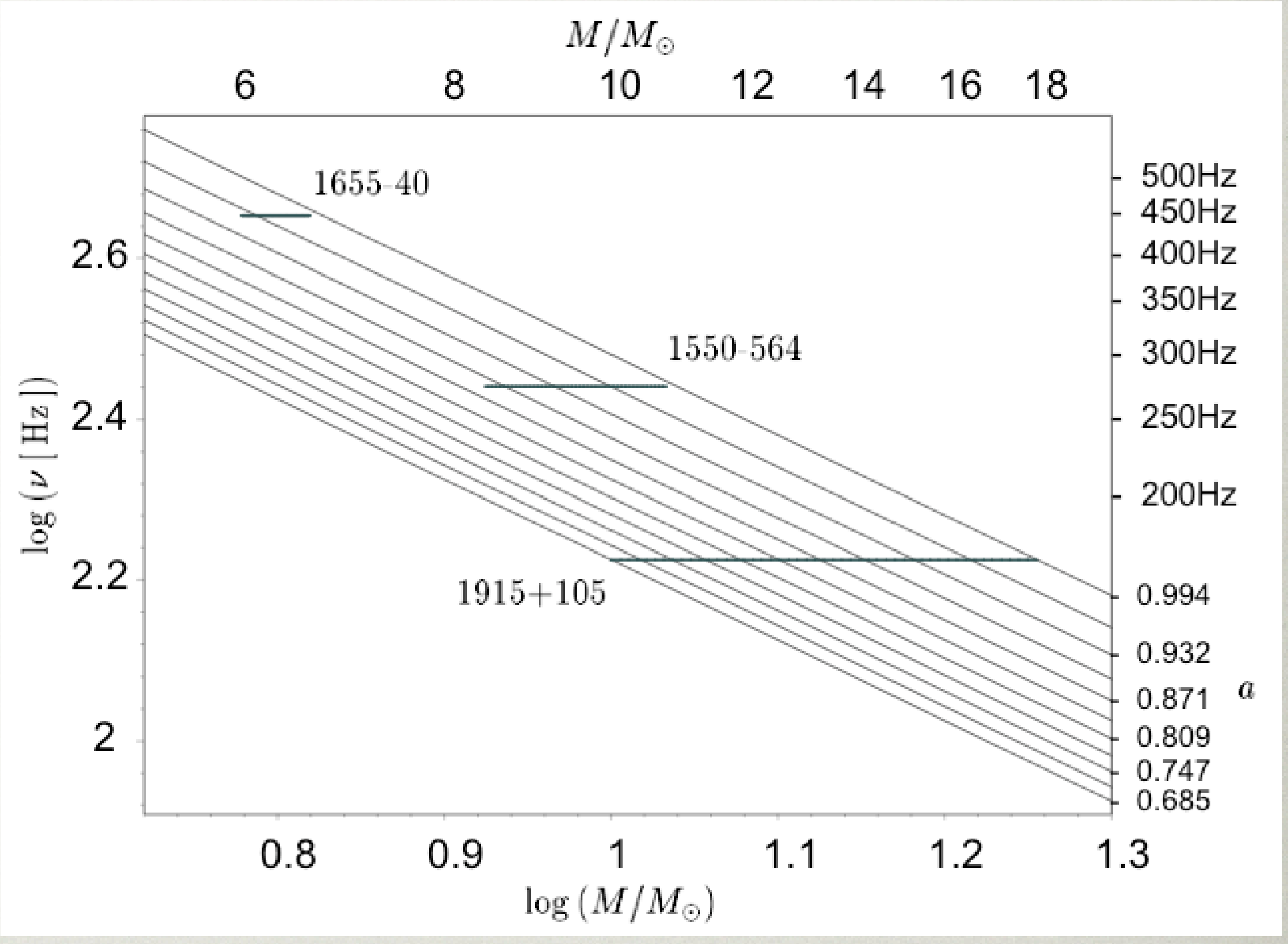
Abramowicz & Kluzniak (2004)

Relativistic resonance

All resonant frequencies scale with 1/M

Prospect to constrain the BH spin (high spins inferred)

Application to ULXs to determine the mass of the accreting object

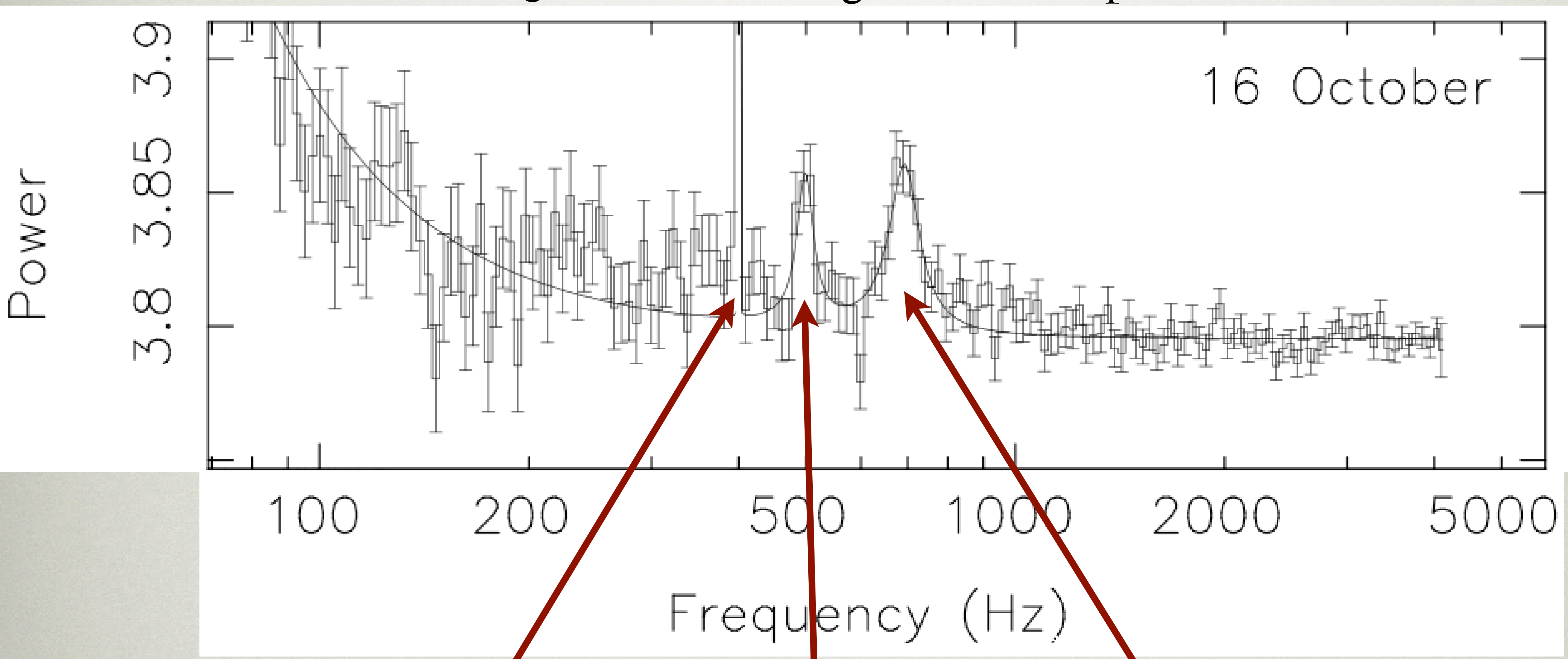


Illustrates the power of fast X-ray timing

Abramowicz & Kluzniak (2004)

Forced resonance

kilo-Hz QPOs in accreting millisecond pulsar



$\nu_{\rm spin} = 401\ \rm Hz$ $\Delta\nu \sim 200\ \rm Hz = \nu_{\rm spin}/2$

Epicyclic frequencies resonate with spin (Wijnands et al. 2003, Kluzniak et al. 2004)
Spin-orbit beat frequency equals vertical epicyclic (Lamb & Miller 2003)

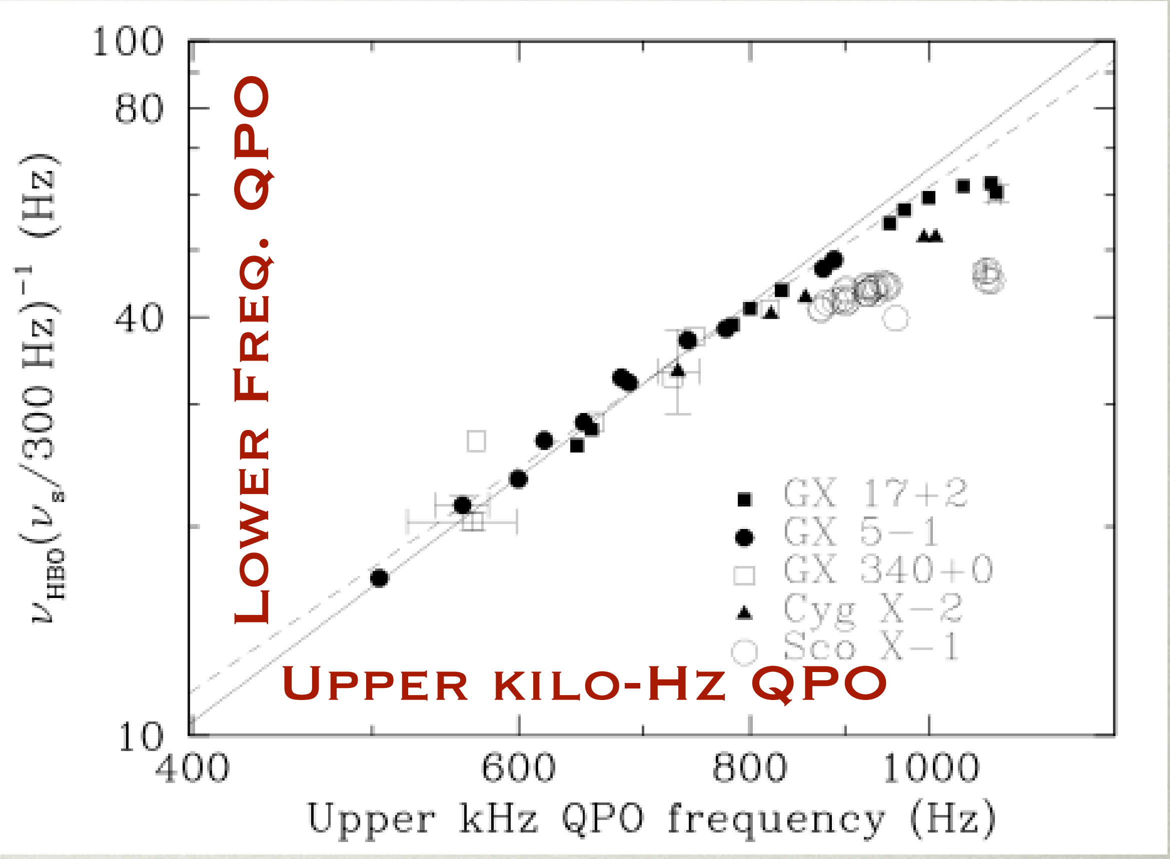
Dragging of inertial frames

- Periastron of eccentric orbit will precess (consequence of the non-$1/r^2$ nature of gravity in GR, similar to Mercury perihelion precession)

- Nodal precession frequency is due to the frame-dragging effect caused by the spin of the central object (Lense-Thirring): $\nu_{\rm nodal} = \nu_\phi - \nu_\theta$

$$\nu_{\rm nodal} \propto (I_{45}/M)(\nu_\phi)^2 \nu_{\rm spin}$$

Neutron stars



But shows deviations and requires large ratio I_{45}/M (I_{45} NS moment of inertia)

Van der Klis (2004)

Beyond RXTE

Beyond RXTE

- We have observed orbital motions in the strong field region
- Key questions arising:
  - Have we detected the ISCO?
  - Have we detected epicyclic frequencies?
  - Have we detected the effects of strong frame-dragging?
- Evidence has been accumulated that the answers to these questions is very likely yes !
- Next step is to get definite answers and start doing true astrophysics with black holes

Motion in strong gravity

- Orbital motion could be further demonstrated:
  - with independent measurements of radius and frequency through e.g. time resolved spectroscopy of the oscillation
  - with simultaneous measurements of orbital and epicyclic frequencies (and whenever possible the spin)
  - with measurements of the frequency ceiling predicted at the ISCO
- Point to the requirement to increase the timing and spectral capability of fast X-ray timing studies

Counts is what counts

$$n_\sigma \propto \mathrm{S}\ \mathrm{rms}^2\ \sqrt{\mathrm{T}}$$

S: source count rate
rms: QPO amplitude
T: Integration time

The 5 PCA units give 0.7 m2 over 3 to 50 keV

20 times more counts with the current XEUS optics

$$5\mathrm{n}_\sigma(\mathrm{PCA}) \longrightarrow 100\mathrm{n}_\sigma(10\mathrm{m}^2)$$

$$\mathrm{T}(5\mathrm{n}_\sigma(\mathrm{PCA})) \longrightarrow \mathrm{T}/400(5\mathrm{n}_\sigma(10\mathrm{m}^2))$$

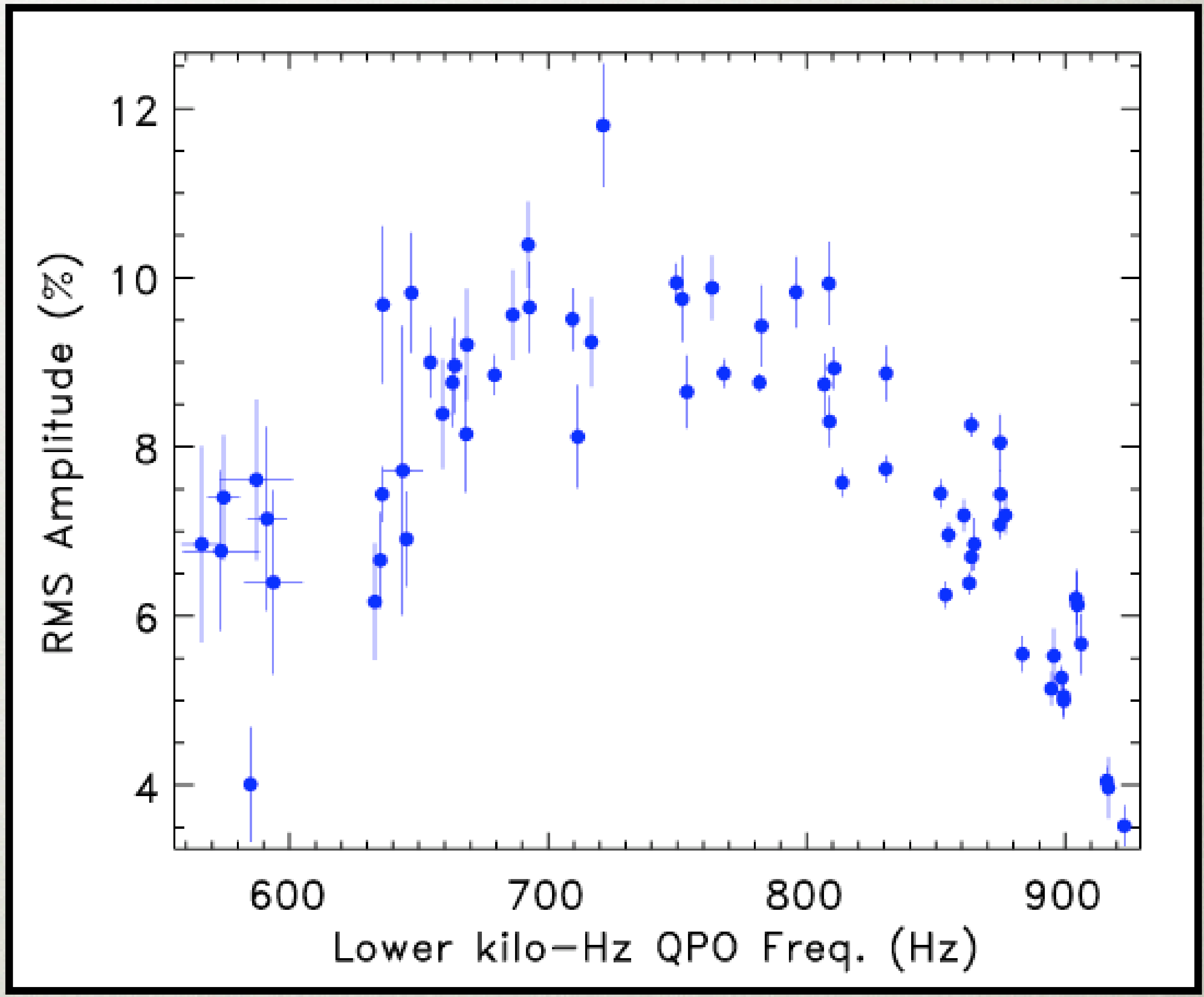
Probing Orbital motion

Ability to detect weak sidebands predicted in many models

Extend QPO search - up to ISCO frequency

Detect QPOs on their coherence times - waveform fitting

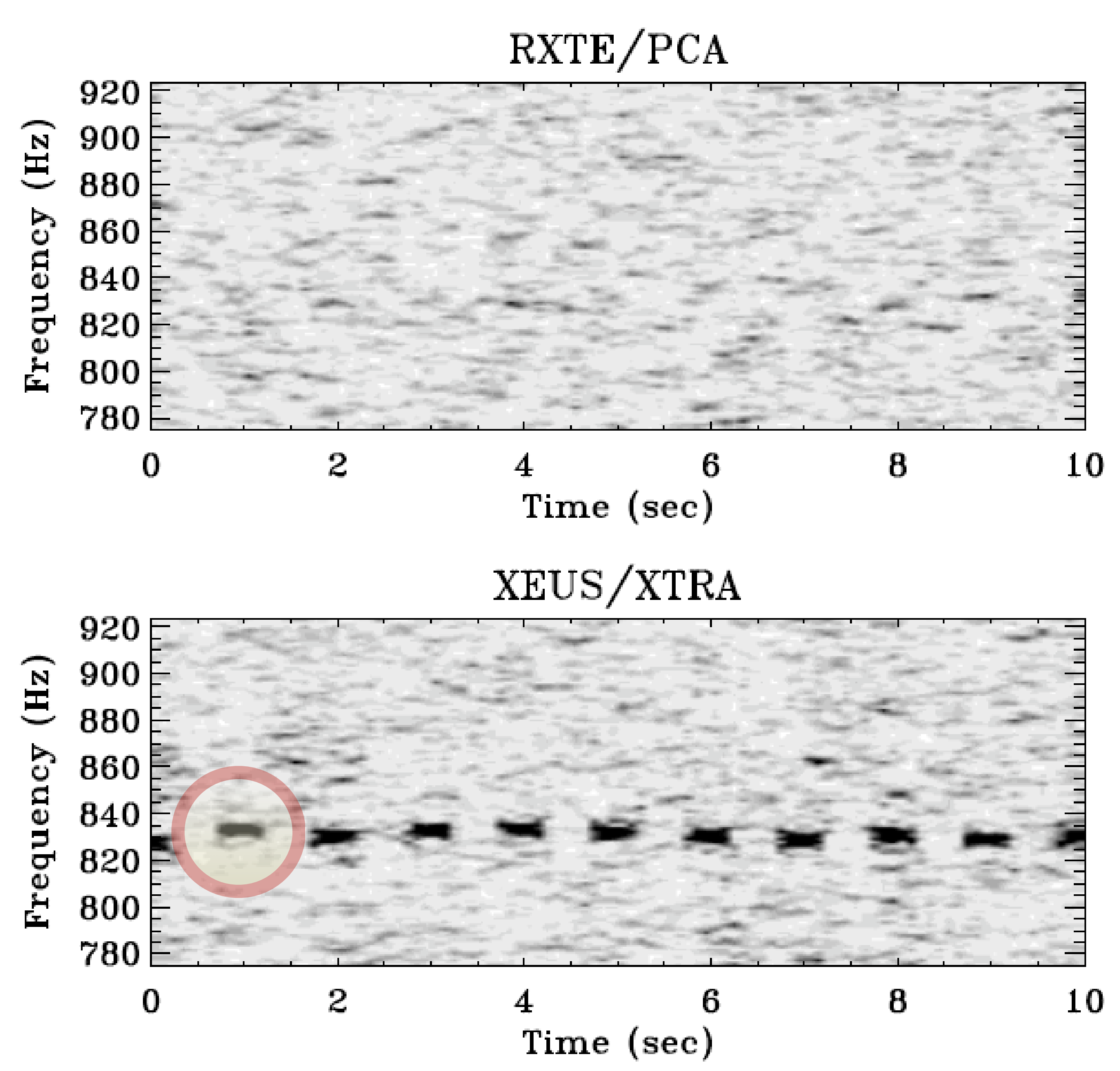
Will require working in parallel on QPO models (GRMHD simulations) and data analysis techniques



Barret et al. (2005)

Time resolved spectroscopy

QPO=series of finite lifetime wavetrains



Conclusions

- Understanding strong gravity is a holy grail for moderm physics: It must be tackled by several independent techniques
- Fast X-ray timing is a powerful approach to probe strong gravitational fields. Highly complementary to other techniques
- The high-frequency phenomena discovered by RXTE (the tip of the iceberg) are in most models associated with strong field effects
- A ~10m^2 collecting area will provide the leap in sensitivity needed to turn these diagnostics into tests, but requires an instrumentation capable of coping with extremely high count rates

Hardware

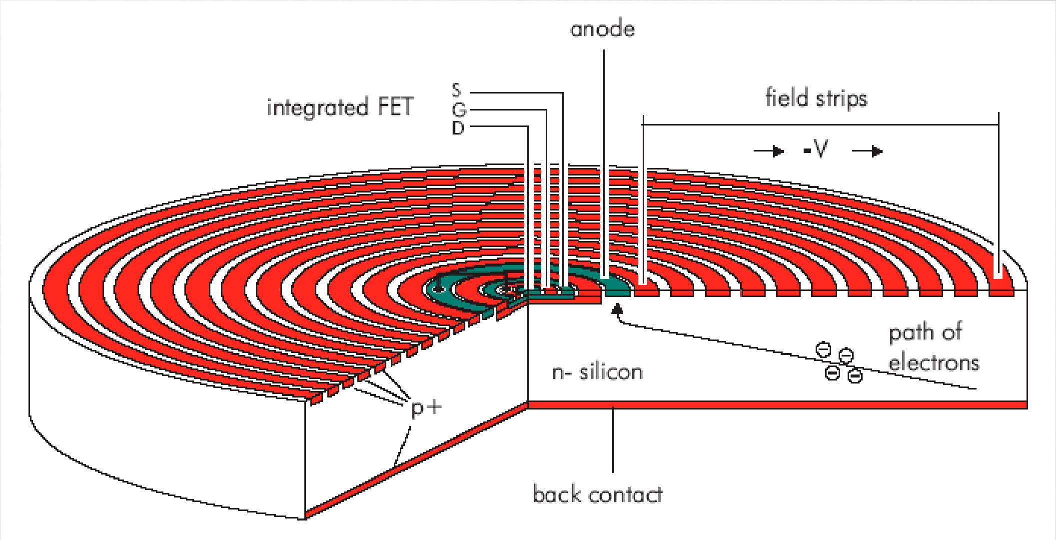
Described in the XEUS instrument Working Report (2004)

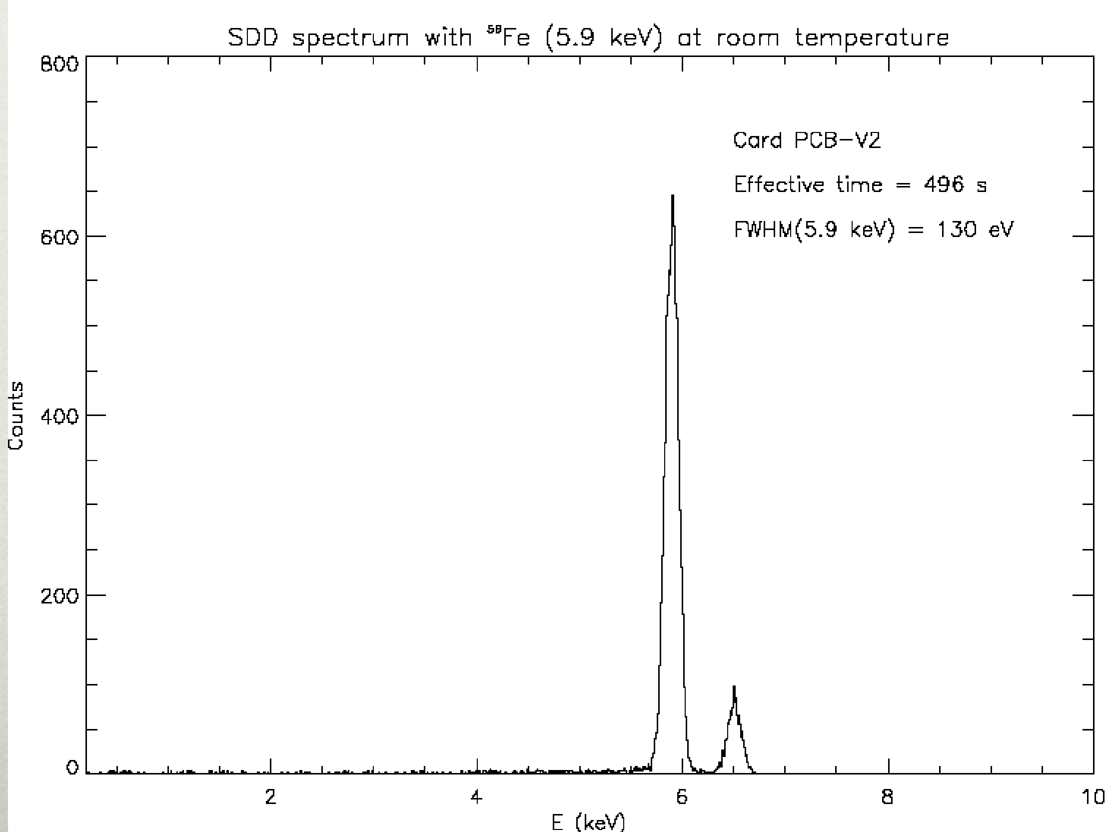
Requirements

- $10m^2$ collecting area - from ~1 keV to ~50 keV (factor of 15 -20 increase in counting rate over the RXTE/PCA)
- 10 microsecond time resolution
- Ability to observe a 5 Mcts/s source (equivalent to 5 Crab)

Silicon Drift Detector

- High resistivity n-type fully depleted Silicon
- Small output capacitance due to the small size of the anode
- High count rate capabilities
- Good energy resolution (130 eV at room temperature)
- Space proven - flew on Mars/Rover

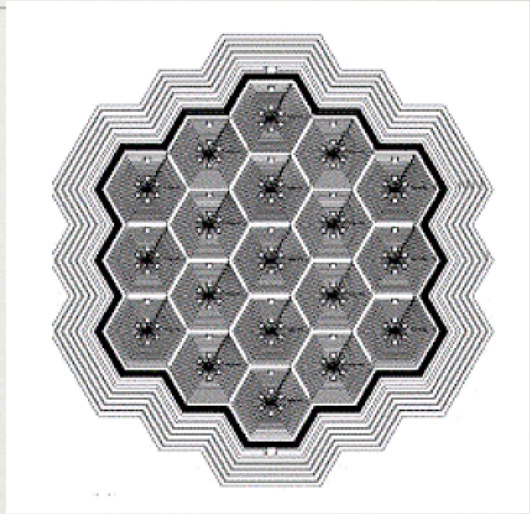


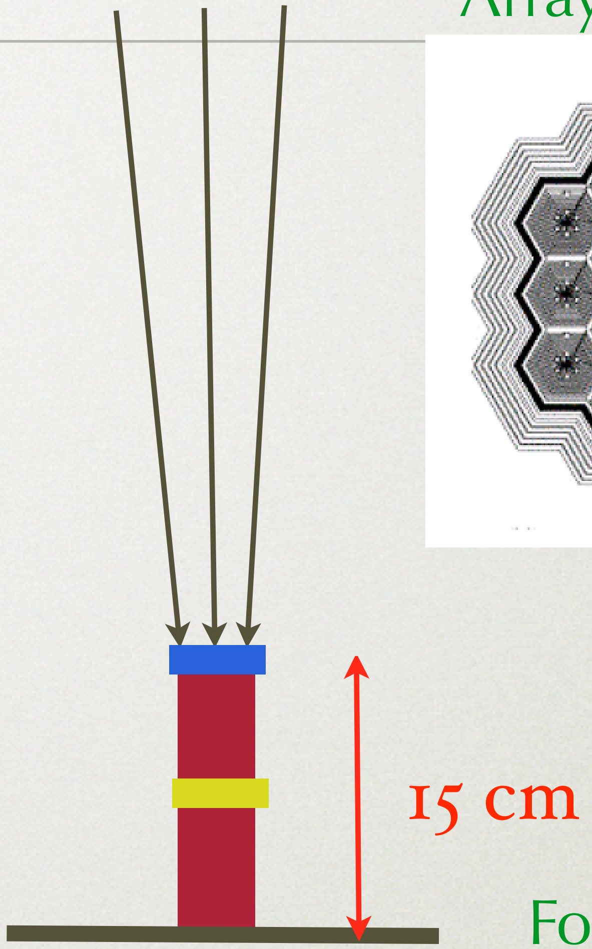


Implementation

- Array of 19 SDDs operated out of focus
- Electronics studied (deadtime control) at CESR with ROENTEC/MPI/MPE with funding from French Space Agency

Array of 19 SDD





Focal plane